

NON-THERMAL EMISSION AND DYNAMICAL STATE OF MASSIVE GALAXY CLUSTERS FROM *CLASH* SAMPLE

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Abstract. Massive galaxy clusters are the most violent large scale structures undergoing merger events in the Universe. Based upon their morphological properties in X-rays, they are classified as un-relaxed and relaxed clusters and often host (a fraction of them) different types of non-thermal radio emitting components, viz., ‘haloes’, ‘mini-haloes’, ‘relics’ and ‘phoenix’ within their Intra Cluster Medium (ICM). The radio haloes show steep ($\alpha = -1.2$) and ultra steep ($\alpha < -1.5$) spectral properties at low radio frequencies, giving important insights on the merger (pre or post) state of the cluster. Ultra steep spectrum radio halo emissions are rare and expected to be the dominating population to be discovered via LOFAR and SKA in the future. Further, the distribution of matter (morphological information), alignment of hot X-ray emitting gas from the ICM with the total mass (dark + baryonic matter) and the bright cluster galaxy (BCG) is generally used to study the dynamical state of the cluster. We present here a multi wavelength study on 14 massive clusters from the CLASH survey and show the correlation between the state of their merger in X-ray and spectral properties (1.4 GHz - 150 MHz) at radio wavelengths. Using the optical data we also discuss about the gas-mass alignment, in order to understand the interplay between dark and baryonic matter in massive galaxy clusters.

Keywords: Clusters: lensing:individual: CLASH - intracluster medium: radio: X-ray - dark matter

1 Introduction

Galaxy clusters are multiple gravitationally bound systems in our Universe that exist at the dense nodal regions of the cosmic web. They are continuously fed with galaxy groups, sub clusters, gas, dust etc. via filaments, giving rise to massive systems of the order of $10^{15} M_{\odot}$. While $\sim 70 - 80\%$ of the total mass in massive galaxy clusters is dominated by dark matter, followed by $\sim 15 - 20\%$ of hot gas ($T \sim 10^8 K$) in the ICM, the remaining is in the form of a few percent of baryonic matter in the galaxies. The dark matter dominates the cluster potential and is expected to be interacting through gravity only, thus collision less. While, the in-falling baryonic matter in the central region of galaxy clusters undergoes mergers that dissipate a huge amount of energy giving rise to turbulence, cold fronts and shocks within the ICM. The dissipated energy causes heating of the ICM gas that emits in X-rays via thermal bremsstrahlung radiation and accelerates the cosmic ray electrons within the ICM upto relativistic energies giving rise to non-thermal radio synchrotron radiation in the presence of magnetic fields (Brunetti et al. 2014).

Depending upon the intensity of merger activity within the cluster central region, the non-thermal synchrotron emission can be classified into strongly polarized peripheral ‘relics’ (a few kpc - Mpc scale) and central ‘Phoenix’ (a few kpc scale) caused via shocks or compression respectively, encountered within the ICM. In addition, the turbulence caused via mergers or gas sloshing gives rise to central unpolarized haloes (> 500 kpc upto

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Table 1. Multi wavelength properties of CLASH clusters

Source	z	X-ray morphology	L_{Bol}^* $10^{44} \text{ erg s}^{-1}$	$Temp^*$ keV	sub groups, BCG	Radio morphology	α_{Halo}
Non cool-core clusters							
MACS J0416.1 – 2403	0.39	extended	16.0 ± 0.9	7.5 ± 0.8	4,2	Halo (USSR)	$\alpha_{235}^{1400} = -1.50 \pm 0.80^a$
MACS J1149.5 + 2223	0.54	extended	30.2 ± 1.2	8.7 ± 0.9	4,1	Halo (Giant USSR) + Relic	$\alpha_{235}^{1400} = -2.10 \pm 0.22^a$
MACS J0717.5 + 3745	0.55	extended	55.8 ± 1.1	12.5 ± 0.7	5, multiple	Halo (Giant) + Phoenix	$\alpha_{235}^{1400} = -0.98 \pm 0.03^a$
Cool-core Clusters							
RX J1532.9 + 3021	0.36	compact	20.5 ± 0.9	5.5 ± 0.4	1,1	mini-Halo	$\alpha_{235}^{1400} = -1.10 \pm 0.07^a$
MACS J0329.7 – 0211	0.45	compact	17.0 ± 0.6	8.0 ± 0.5	1,1	mini-Halo (USSR)	$\alpha_{610}^{1400} = -2.40 \pm 0.04^a$
MACS J1931.8 – 2635	0.35	compact	20.9 ± 0.6	6.7 ± 0.4	1,1	mini-Halo? (USSR)	$\alpha_{235}^{1400} = -2.10 \pm 0.10^b$
RX J2129.7 + 0005	0.23	compact	11.4 ± 2.0	5.8 ± 0.4	1,1	mini-Halo	$\alpha_{235}^{1400} = -0.60 \pm 0.00^c$
RX J1347.5 – 1145	0.45	compact	90.8 ± 1.0	15.5 ± 0.6	1,1	mini-Halo	$\alpha_{235}^{1400} = -0.92 \pm 0.03^d$
MACS J1206.2 – 0847	0.44	compact	43.0 ± 1.0	10.8 ± 0.6	1,1	mini-Halo ^{e?}	-
MACS J1115.9 + 0129	0.35	compact	21.1 ± 0.4	8.0 ± 0.4	1,1	mini-Halo (USSR)	$\alpha_{235}^{1400} = -1.80 \pm 0.20^a$
Abell 611	0.29	compact	11.7 ± 0.2	7.9 ± 0.3	1,1	No detection ^c	-
Abell 1423	0.21	compact	7.8 ± 0.2	7.1 ± 0.6	1,1	No detection ^c	-
Abell 2261	0.22	compact	18.0 ± 0.2	7.6 ± 0.3	1,1	No detection ^c	-
Abell 209	0.21	slightly extended	12.7 ± 0.3	7.3 ± 0.54	1,1	Halo (Giant)	$\alpha_{610}^{1400} = -1.20 \pm 0.20^f$

*: Postman et al. 2012, a: Pandey-Pommier et al. 2016, 2014, 2013, b: Giacintucci et al. 2014, c: Kale et al. 2013, 2015, d: Gitti et al. 2007, e: Young et al. 2015, f: Venturi et al. 2008

1 Mpc scale) in unrelaxed elongated ‘non cool clusters’ (NCC) and mini-haloes (< 500 kpc) in relaxed compact ‘cool clusters’ (CC), respectively. CC clusters tend to host a central bright radio loud BCG, while NCC clusters host multiple ellipticals in their center associated to each sub group under collision. In spite of more than 100s of radio detection to-date of the diffuse synchrotron emission from the ICM in massive galaxy clusters, their origin still remains unclear (Ferreti et al. 2012). Thus multi wavelength study is extremely important in order to unravel the correlation between the dynamical state of the cluster and the origin of the non-thermal emission from their ICM.

2 Dynamical state and Non-thermal emission in massive galaxy clusters

In this paper we present radio analysis on a sample of 14 massive CLASH clusters (Table 1) (Postman et al. 2012) where deep Giant Metrewave Radio Telescope (GMRT) observations are available. The low frequency radio observations (+ archive and TGSS survey) with the GMRT down to 150 MHz has confirmed detection of radio haloes, mini-haloes and emission from the BCG in all the 14 systems. Combined high frequency data at 1.4 GHz with the Very Large Array (VLA) has been used to derive their spectral information. These clusters are very luminous ($L_{Bol} = 10^{44} \text{ erg s}^{-1}$, $T > 5 \text{ keV}$) at X-ray wavelength and show lensing properties at optical wavelength. The result of our multi wavelength analysis are listed below and in Table 1:

- 3 merging NCC massive clusters hosts radio haloes that trace the extent of X-ray emission along with the shock regions (phoenix and relics) and radio emission from the BCGs.
- MACS J0416.1 – 2403 shows 2 bright BCGs and multiple sub-groups under collision with an Ultra Steep Spectrum Radio (USSR) halo (Fig. 1) ($S_\nu = \nu^\alpha$, $\alpha < -1.5$, where S is the flux density (mJy), ν the frequency (MHz) and α the spectral index). The USSRH are rare population of radio haloes that are relatively brighter at lower frequencies and caused by non-thermal emission from the population of old electrons after the less-common post-major merger or more frequent and less energetic pre-minor merger events in the Universe (Pandey-Pommier et al. 2015, Ogrea et al 2015, Cassano et al. 2010). These USSR haloes have low surface brightness and are expected to be the dominant population that will be discovered via new generation low frequency interferometer arrays like LOW Frequency ARray (LOFAR) and Square Kilometer Array (SKA), thanks to their high (μJy) sensitivity and resolution (arcsec) at MHz-range (Cassano et al. 2015).
- MACS J1149.5 + 2223 shows a bright BCG in the center and multiple sub-groups undergoing collision. It hosts a possible giant USSR halo with shocked relic region (refer Fig.1), suggesting a post violent merger phase (Bonafede et al. 2013, Pandey-Pommier et al. 2016, Golovich et al. 2016).

- MACS J0717.5 + 3745 shows multiple bright galaxies associated to several sub-groups under collision in the center of the cluster. It hosts the most powerful giant radio halo ($\alpha > -1.2$) known in galaxy clusters and a shocked phoenix region at the center (Fig. 1, Pandey-Pommier et al. 2013, van Weeren et al. 2008). The spectral and dynamical properties of the cluster suggest that its in a state of on-going merger.
- 11 CC massive clusters in our list either host mini-haloes or emission from the central radio loud BCG. Using high resolution observations (2") at 1.4 GHz and low resolution observation down to 150 MHz, we were able to marginally differentiate the emission from the jet of the AGN as well as the mini-halo.
- 3 CC clusters (RXJ1532.9 + 3021, RXJ2129.7 + 0005, RXJ1347.5 – 1145) show one central bright BCG and a radio mini-halo caused due to gas sloshing in the central region with $\alpha > -1.2$ as shown in Fig. 2 top panel (Pandey-Pommier et al. 2016, Kale et al. 2013, 2015, Gitti et al. 2007). These clusters are in relaxed state with on-going minor merger activities.
- 3 CC clusters (MACS J1115.9 + 0129, MACSJ0329.7 – 0211, MACSJ1931.8 – 2635) show one central bright BCG and rare USSR mini-haloes with $\alpha < -1.5$ as seen in Fig. 2 bottom panel, indicating that these clusters are entering a post merger phase, with the population of old electrons mainly emitting at lower frequencies (Pandey-Pommier et al. 2016, Giacintucci et al. 2014).
- 4 CC clusters (MACSJ1206.2 – 0847, Abell 611, Abell 1423, Abell 2261) show a bright BCG with no associated mini-halo emission, however emission from the central BCG is clearly detected in these clusters. In the case of MACSJ1206.2 – 0847, diffuse radio emission was detected a few arsec away from the central BCG, suggesting the presence of a possible mini-halo, however deep radio observations are needed to confirm this result (Young et al. 2007, Kale et al. 2013, 2015) An upper limit derived from the GMRT maps are plotted in Fig. 3, top panel for the mini-haloes and the BCGs. The non detection of mini-haloes indicates that the cluster has entered a relaxed state with no further merger activity in process.
- Abell 209 shows a giant radio halo and an associated central bright BCG, refer Fig. 3, bottom panel. This CC cluster is exceptional with slightly extended morphology indicating the end of a massive merger stage or a beginning of a relaxed phase (Venturi et al. 2008).

3 Gas-mass alignment and interplay between dark and baryonic matter in massive galaxy clusters

The multiple probes (X-ray, radio, BCG) of matter distribution in galaxy clusters can be used to study their gas-mass alignment as well as the interaction between their dark and baryonic matter. Dark matter dominating the cluster gravitational potential, binds the hot, X-ray emitting and non-thermal radio emitting intra cluster gas to the cluster center. While CC clusters tend to show homogeneous distribution in the total mass map

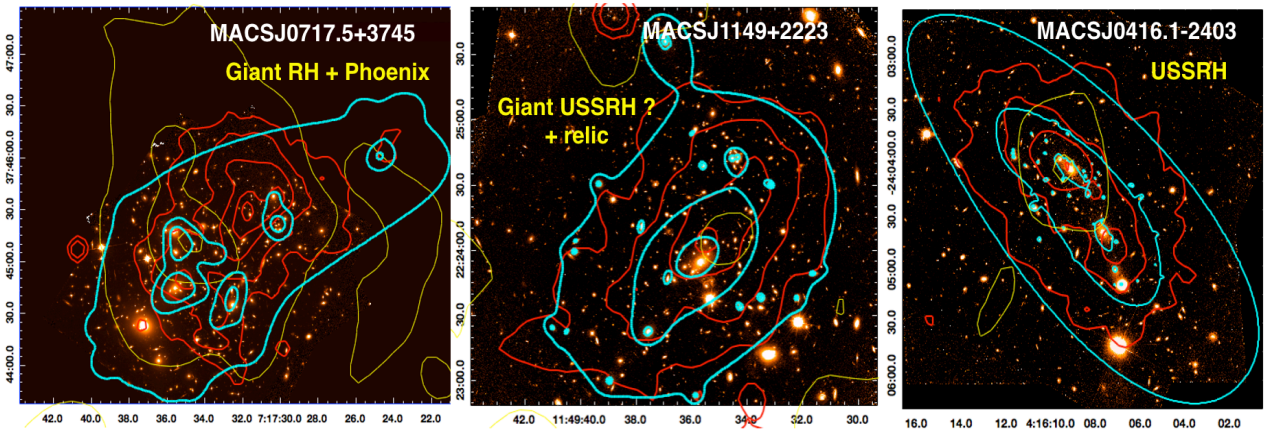


Fig. 1. Dark and baryonic matter coupling in NCC clusters. X-ray (red), HST total mass map (cyan) and GMRT (yellow) contours are overlaid on background HST map. The radio haloes are marked as ‘RH’ and Ultra steep spectrum radio haloes as ‘USSRH’. The total mass map for MACS J0416.1 – 2403 is constructed with MUSE data.

(dark + baryonic matter, constructed from the HST/MUSE data) and positional coincidence in the central baryonic mass concentration versus the Centroid of the cluster, the NCC often show in-homogeneous total mass distribution with non-coincidence (offset) in the central baryonic mass concentration versus the Centroid (Limousin et al. 2012). This is mainly due to the violent dynamical interaction in the NCC clusters, that produces shocks or pressure waves disturbing the gas (Cassano et al. 2010). In the following section we will discuss the interaction of dark and baryonic matter in our sample of 14 massive CLASH clusters.

- The baryonic matter (X-ray + radio emitting gas and BCG) in 3 NCC massive clusters namely, MACS *J0717.5+3745*, MACS *J1149.5+2223* and MACS *J0416.1-2403* shows no well defined center or positional coincidence in the multi wavelength data. In the case of MACS *J0416.1-2403*, the total mass map was constructed with the MUSE data providing a better constraint on the extent of the cluster mass, thanks to its high sensitivity to detect faint sources (refer Fig. 1, last panel). Further, a shift (a few arcsec) in the peak of optical total mass map, X-ray peak from the thermal gas and radio peak from the non-thermal gas in the ICM is detected, suggesting an ongoing merger activity in these clusters (refer Fig. 1). The shift in the peak also indicates the decoupling of dark matter and baryonic matter gas components suggesting a post-merger scenario for MACS *J1149.5+2223* and MACS *J0416.1-2403* clusters with USSR haloes and on-going merger scenario for MACS *J0717.5+3745* cluster with less- steep radio halo.
- In the case of 6 (RX *J1532+3021*, RX *J2129+0005*, RX *J1347-1145*, MACS *J1115+0129*, MACS *J1931-2635*, MACS *J0329-0211*) CC clusters the central region shows aligned X-ray, radio and total mass peak, suggesting that the clusters are in relaxed phase with minor merger activity and coupled dark and baryonic matter (Fig. 2).

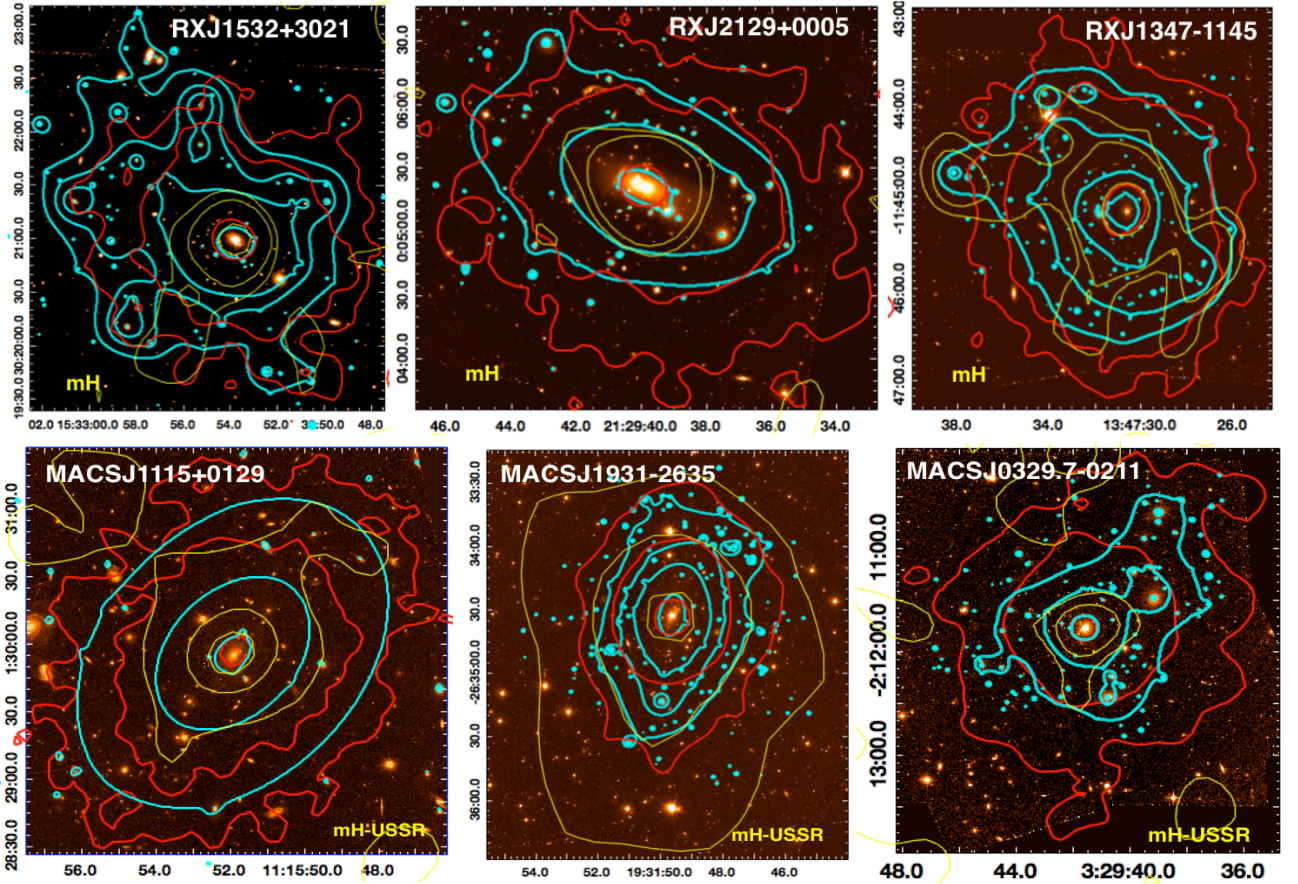


Fig. 2. Dark and baryonic matter coupling in CC galaxy clusters. X-ray (red), HST total mass map (cyan) and GMRT (yellow) contours are overlaid on background HST map. The mini-haloes are marked as ‘mH’ and Ultra steep spectrum radio mini-haloes as ‘mH-USSR’.

- In the case of 4 CC clusters a coincidence in the peaks of X-ray and total mass map is seen. The radio emission from the BCG, wherever detected is aligned with the X-ray/total mass map peak, suggesting no more on-going merger activity (refer Fig. 3).
- Finally, the exceptional CC cluster Abell 209 hosting a giant radio halo shows an offset in the peak of radio and total mass map with a coincidence in the peak of total mass and X-ray (Fig. 3, bottom middle panel), suggesting its transition stage from the NCC to CC phase. The cluster appears to be cooling down after a violent merger phase.
- The morphological and spectral information from the multi wavelength data was used to infer the state of relaxation of galaxy clusters as well as the interplay between their dark and baryonic matter. The X-ray and total mass map concentration (ratio between the light within a circular aperture of minimum 100 kpc and maximum 500 kpc) of each cluster in our list is plotted with respect to the shift in their X-ray Centroid (standard deviation of the projected separation between the X-ray peak and Centroid estimated within circular aperture of maximum 500 kpc) in Fig. 3, bottom right panel. It is clear from the figure that the concentration of CC clusters is higher near the central region and they show smaller shift in their X-ray Centroid compared to the NCC clusters, confirming their non relaxed nature. Further, the mass concentration in X-rays is higher in general for both the CC and NCC clusters compared to the total mass map (with dominating dark matter) derived from the optical data, confirming the collisional nature of the baryonic matter traced via X-ray observations at the cluster center. The lower mass concentration at the cluster center in the total mass map suggests its collision less nature, thus minimally affected via merger events.

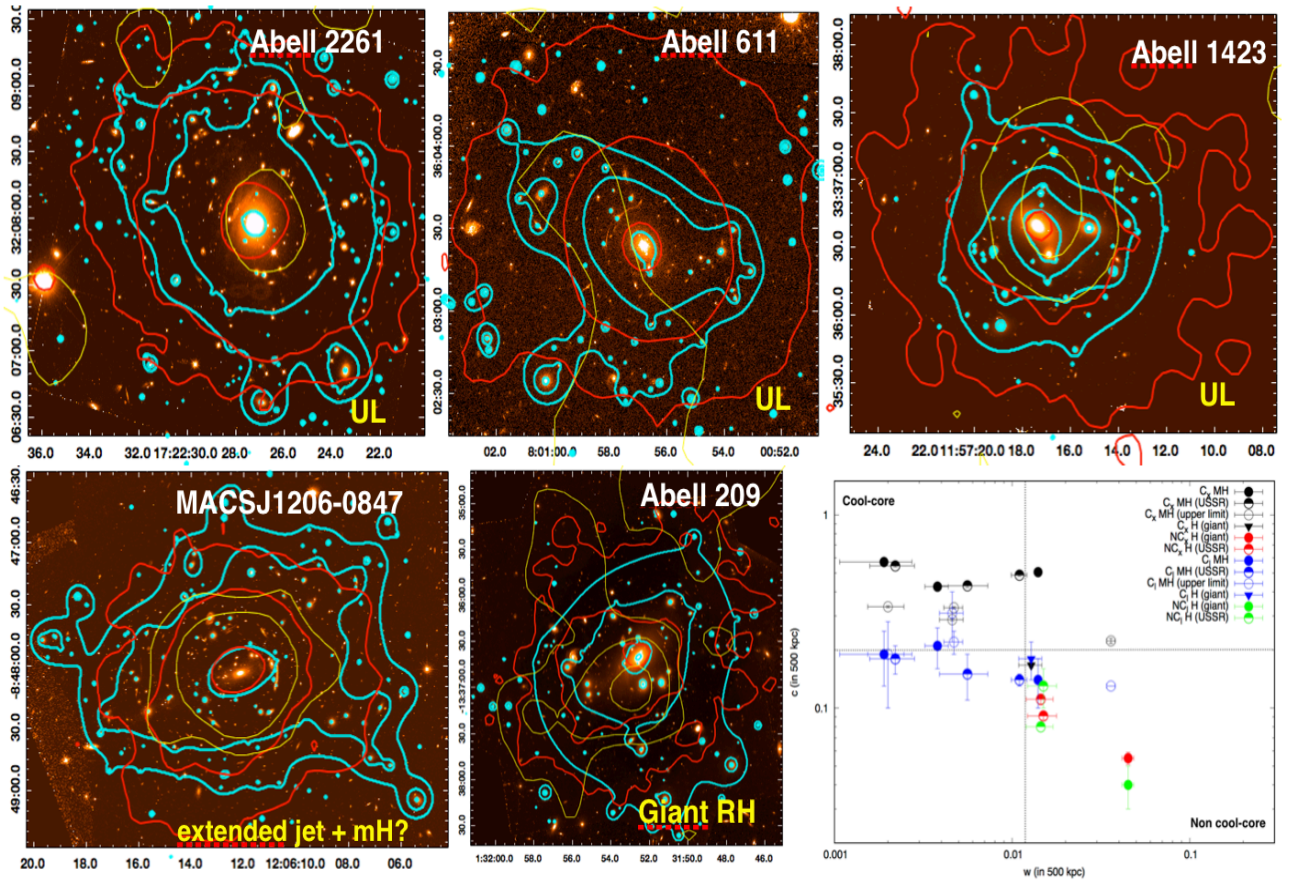


Fig. 3. Dark and baryonic matter coupling in CC galaxy clusters. X-ray (red), HST total mass map (cyan) and GMRT (yellow) contours are overlaid on background HST map. The non-detection upper limits are marked as ‘UL’, radio halo as ‘RH’, X-ray concentration in cool-core as ‘ C_x ’, X-ray concentration in non cool-core as ‘ NC_x ’, Concentration in total mass map via lensing analysis as ‘ C_l ’ in cool-cores and ‘ NC_l ’ in non cool-core clusters.

4 Conclusions

Massive galaxy clusters provide the most interesting astrophysical laboratories to study the merger activity and emission processes in the dense regions of the Universe. In this paper, we present a multi wavelength (GMRT, Chandra, HST/MUSE) analysis of morphological and spectral properties on a sample of 14 massive galaxy clusters in the CLASH catalog. The multi wavelength data was used to derive a correlation between the dynamical state and the non-thermal emission from the cluster ICM and study the dark and baryonic matter interaction in their central region. The main results derived in this paper are listed below:

- Low frequency observations (down to 235 or 150 MHz) not only confirm the presence of mini-haloes and haloes in massive galaxy clusters but also provide information about their dynamical state.
- Radio morphology gives the information about the violent or less energetic merger activity in the cluster and the spectral index gives information about the pre- or post- merger state of the cluster.
- The radio (non-thermal) halo and X-ray (thermal) emission are generally coincident and originate from the ICM.
- The peak in mass distribution at X-ray and total mass map is coincident for CC clusters while non-coincident in NCC clusters.
- An offset in the peak of radio and total mass map as well as X-ray is detected in clusters hosting haloes, where the merger is still active.
- Combined multi wavelength analysis of the mass distribution in galaxy clusters suggests that dark matter is loosely interacting while the baryonic matter is tightly interacting during merger events in the cluster central regions.

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